

Absolute calibration of microchannel plate detector for carbon ions up to 250 MeV

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A 375TW 40fs pulse was used at the ASTRA GEMINI facility located at the Rutherford Appleton Laboratory U.K. for investigating novel ion acceleration regimes employing ultrathin foil targets. An online detection system consisting of a Thomson Parabola Spectrometer (TPS) — Microchannel Plate (MCP) was used to determine maximum energies and spectra per species. The response of the MCP was calibrated for absolute particle (carbon) number per steradian using CR-39 up to 21 MeV/nucleon. This calibration provides a useful reference for a widely used diagnostic arrangement.

1 Introduction

Ion acceleration from high intensity ($> 10^{18}$ W/cm²) lasers has been extensively explored using a variety of laser and target parameters as a means of generating high energy, short duration (ps) ion bursts. Most of the focus has been towards Target Normal Sheath Acceleration (TNSA) generating short pulses of 10s of MeV multi-species ions from the target bulk and rear contaminants [1]. This is typically done using targets with thickness of a few microns, where ions are accelerated by the strong sheath field (order of TV/m) created by the hot electrons at the target surfaces.

Theoretical and numerical investigations suggest that for the next generation of lasers with higher intensities ($> 10^{22}$ W/cm²), radiation pressure acceleration (RPA) will begin to dominate, potentially achieving ion energies in the 100s of MeV to GeV range [2]. Recent studies have shown that RPA can become the dominant acceleration mechanism already at current intensities by careful control of the target thickness and polarization of the laser [3]. Significant attention has been devoted recently to the development of laser driven ion accelerators as a compact source of high energy ions with clinical interest [4, 5] which motivates the effort in understanding and characterising these beams.

Laser-based ion acceleration experiments routinely utilize absolutely calibrated detectors such as radiochromic film (RCF), CR-39 (Columbia Resin 39, a solid-state track detector) and Image plates (IP), detailed in [6]. These are used either in a stack arrangement [7] or, in the case of IP or CR-39, in the detection plane of a Thomson Parabola Spectrometer (TPS). Calibrations for these detectors exist up to 10s of MeV for protons and heavier ions [8–10]. The detectors are typically deployed within the evacuated interaction chamber and thus only after breaking vacuum and processing the detector, information on the energies achieved in a shot can be obtained. This delay can be removed with the use of online detectors such as MCPs, which provide a real-time response and can be operated without breaking the vacuum in the chamber.

We report here on the calibration of a MCP assembly up to 21 MeV/u (252 MeV) for C⁶⁺ under conditions of relevance to irradiation of ultrathin foil investigations similar to those reported in [3]. The calibration data was collected in a follow up experiment aiming to extend the previous dataset and to advance our understanding of radiation pressure acceleration, and its dependence on target thickness and laser polarization.

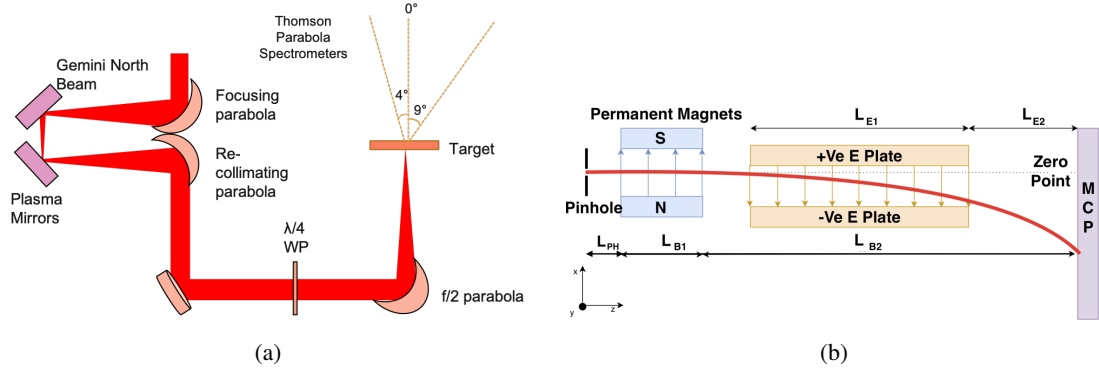


Figure 1. (a) Experimental set-up using double plasma mirror arrangement in the GEMINI target area (b) 0° TPS Dimensions: $L_{PH} = 67$ mm, $L_{B1} = 50$ mm, $L_{B2} = 555$ mm, $L_{E1} = 200$ mm, $L_{E2} = 335$ mm, Pinhole Size = 0.4 mm, B Field Strength = 0.972 T, E field Strength = 25 kV/cm

2 Experiment

2.1 Experimental set-up

The experiment was set up as shown in figure 1(a), using a double plasma mirror configuration to produce a contrast $< 10^{-12}$ on the nanosecond timescale in order to preserve the integrity of the foils; this reduces the amount of front surface expansion before the main pulse arrives providing a steep density gradient for the interaction. The beam passed through a quarter wave plate, used to alter the polarization between linear and circular. The beam was focused using the f/2 parabola and incident at 0° on target. This produced ~6J on target and an intensity of $\sim 5 \times 10^{20}$ W/cm². Amorphous carbon targets 2–100 nm thick were used. The diagnostic set-up was optimized for the detection of high energy carbon ions and protons, with a TPS, as expected from bulk acceleration in the ultra-thin target regime. To improve the number of shots that could be taken between chamber cycles (replacing targets and other detectors), MCPs were used as the detectors to record the particle spectra. A calibration for this detector was an objective for present and future use, as required in order to achieve quantitative information on the ion spectra.

Using the information in figure 1(b) along with the equation (2.1) below, the vertical deflection (S_B) can be associated to a given ion energy (where r_L is the Larmor radius associated with the B field). The electric field separates the species and the deflection (S_E) is given by equation (2.2).

$$S_B = r_L - \sqrt{r_L^2 - L_{B1}^2} + \frac{L_{B1}L_{B2}}{\sqrt{r_L^2 - L_{B1}^2}} \quad (2.1)$$

$$S_E = \frac{qEL_{E1}}{mv_0^2} \left[\frac{L_{E1}}{2} + L_{E2} \right] \frac{r_L^2}{\sqrt{r_L^2 - L_{B1}^2}} \quad (2.2)$$

2.2 MCP detector

The calibration presented was performed using a Hamamatsu MCP F2226-14PF227 on the 0° TPS. This is a 77 mm diameter circular MCP with a thickness of 1 mm and a P47 phosphor screen. The MCP acts as an electron multiplier to incident ionizing radiation where the electrons are accelerated

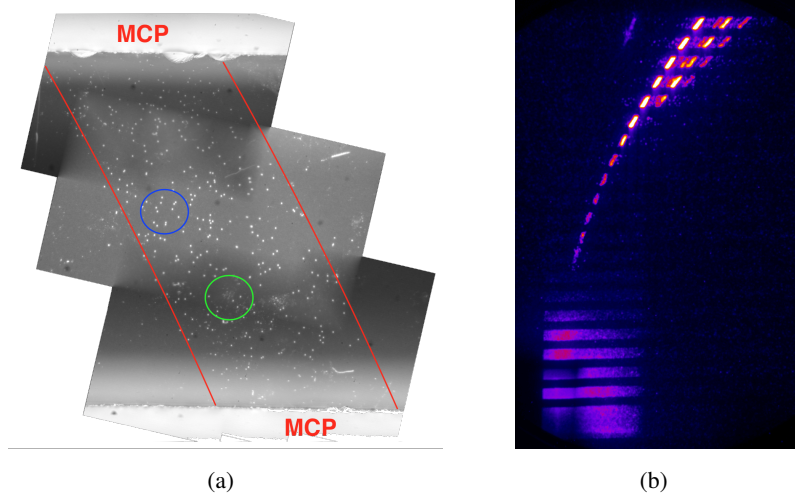


Figure 2. (a) Mosaic image of CR-39 at $\times 10$ magnification showing the width of the parabolic ion trace (red lines) and the CR-39–MCP interface at 4.1 MeV/u (top) and 4.4 MeV/u (bottom). The blue circle represents C^{6+} and green represents noise from damage particles (b) Image of MCP with slotted CR-39 placed in front of it forming regular interfaces between the two.

by a potential difference towards the phosphorous screen. The fluorescence has a 10% decay time of less than 1 ms and this was captured with an Andor Neo CCD with a longer exposure (typically 100 ms) using the same trigger as the laser. With this arrangement, the image can be obtained remotely and immediately after the shot and hence some basic information on the particle beam e.g. a measure of the maximum energy per species, can be obtained almost instantly. The space between the MCP screen and CCD was enclosed and light-tight to remove any background noise.

MCPs require a high vacuum ($< 10^{-6}$ mbar) to safely operate and a large potential difference (3 kV) so that even a small number of incident particles can generate a sufficiently high signal on the phosphorus screen [11]. The response of the MCP to high energy carbon ions has not yet been well characterised, and calibration data exist only for protons and lower energy carbon ions [12, 13]. The response is not necessarily expected to be linear against particle energy due to the large variance in the LET for the different energy ions produced in a single shot. In the context of our experimental program aimed at characterizing RPA, it is useful to extract an energy spectrum in absolute terms in order to identify features associated with the acceleration mechanism, particularly in relation to the carbon ions from the target bulk.

2.3 Calibration

In order to perform the calibration, slotted CR-39 (slot width of 1 mm) was placed in front of the MCP, on the 0° line, on a shot (e.g. figure 2(b)). This calibration procedure, already reported in [12, 13], allows the direct comparison “in-situ” of the two detectors using the laser-accelerated ion signal.

As the carbon ions stop in the 1 mm thick CR-39, they could not reach the MCP. A segment of a parabolic trace will therefore be intercepted by the CR-39, resulting in ‘shadows’ on the MCP signal in correspondence to the CR-39 bars. A signal is produced on the MCP through the slotted gaps.

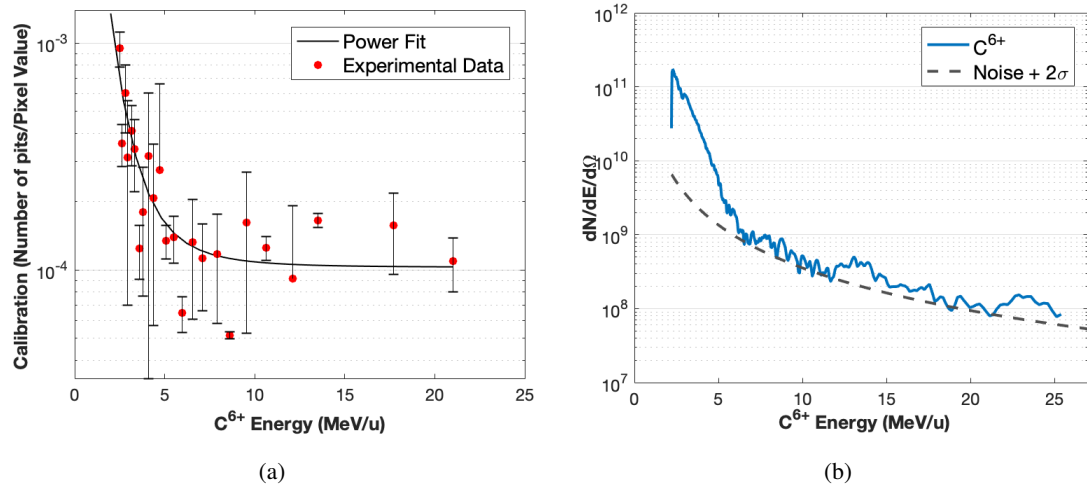


Figure 3. (a) Calibration function for each energy bin for TPS 0° (red dots): Calibration = $1.257 \times 10^{-2} \times \text{energy}^{-3.331} + 1.028 \times 10^{-4}$ (black line) (b) Spectrum for 15 nm amorphous carbon with intensity of $4.7 \times 10^{20} \text{ W/cm}^2$. The maximum energy is 25 MeV/u.

At the interface between the MCP and CR-39, the CCD pixel value and CR-39 carbon pit density can be directly compared. The parabolic trace of carbon ions is now composed of alternating MCP and CR-39 segments at different energies so that a calibration curve can be created using the data at each interface (figure 2(b)). The CR-39 was processed after the experiment by etching it in a 6 M solution of NaOH at 85°C in short intervals. Each bar was then imaged using a microscope and an image of the full ion trace could be built up. The pits could then be counted using the ImageJ software.

The ion trace on the detector has a finite width depending on the size of the pinhole, hence the total particle number at a given energy is the sum of the particle counts across this width. The total pixel value for a particular energy of the parabolic trace is accumulated across the width and compared to the sum of the carbon pits on the corresponding piece of CR-39 to relate the two totals. Since each pixel is equal to 100 μm, each pixel has an associated energy of carbon ion. This resolution was then applied to counting carbon pits in the CR-39, the total number of pits were counted in the first 100 μm from the interface and accumulated. This was then plotted against the energy at the interface and a function produced as seen in figure 3(a) (Calibration = $1.257 \times 10^{-2} \times \text{energy}^{-3.331} + 1.028 \times 10^{-4}$). The response can be seen to be mostly flat above 10 MeV/u which is promising for extending this to higher energies, as it indicates that, even if the particle's Bragg peak is not located within the confines of the MCP, it will still deposit a measurable amount of energy.

The uncertainties associated with each energy bin arise from human error in counting of the pits per energy bin but also due to small scale spectral fluctuations which are detected only on the MCP or CR-39 but not the other. At these points, the MCP image and CR-39 interface would not correspond to the same number of particles and leads to the fluctuations of the calibration above and below the best fit line.

2.4 Spectra

The calibration can then be applied to the sum of the pixel value across the ion trace for every energy to produce an absolute number of particles. By knowing the solid angle of the entrance pinhole of the TPS, in this case 118 nSr, one can produce an absolutely calibrated spectrum in particle number per MeV per steradian. The noise of the detector is also shown in figure 3(b) alongside a C^{6+} spectrum. The maximum ion energy is then determined to be at the point when the ion signal trace is equal to the noise + 2σ . The noise is measured as the signal of a parabolic trace on the detector alongside the carbon signal where there is no ion trace present. A moving average and standard deviation was calculated for this trace and plotted. As mentioned before, previous experiments [3] irradiated similar targets on Gemini but employed Image Plates in the TPS. Using MCPs and similar targets, we are able to quantitatively reproduce these spectra, which confirms the correctness of the calibration. In obtaining particle spectra as in figure 3(b), the calibration was extended to energies higher than 21 MeV/u assuming the same power law.

3 Conclusions

The response of a Thomson Parabola Spectrometer — MCP assembly was calibrated for absolute particle number up to 21 MeV/u. The response is best described using a power law. This has allowed for a calibrated spectrum to be produced for C^{6+} which is a very important measurement for bulk ion acceleration from thin foils. The experiment shows that MCPs provide a promising method of detecting high energy carbon ions and producing spectra from high repetition rate, high power laser systems. Data associated with the research published in this article can be accessed at: <https://doi.org/10.17034/e5ed635c-0cc0-46af-aeaa-782008172d6c>.

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